NUTRIENT BALANCES AND HIGH PRODUCTIVITY

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ABSTRACT

Increased forest production will place greater nutrient demands on some soils than can be met by the natural input processes. Nutrient outputs in excess of input will lead to a decline in productivity on some sites unless action is taken to maintain soil fertility. We cannot predict rates of nutrient decline or the time required for large nutrient removals to effect productivity. Knowledge of site nutrient balance and the development of fertilizer prescription technology offer an effective approach for maintaining and improving site productivity.

Nutrient requirements of forests increase as production per unit area increases. Intensive forestry practices are increasing production, but even greater productivity is needed to meet rapidly expanding demands. Can the soil on a fixed or declining land area provide the nutrients to yield forest products at the level our economy demands? Based on records of the production, an increase in the yield of forests will require improved management, improved trees, and improved soil fertility. We must not only maintain soil fertility; we must improve it.

Natural processes of nutrient input maintain site productivity under low levels of product harvest. A few commercial tree species fix nitrogen in association with microorganisms. For the remaining species, it is now generally recognized that whole-tree harvesting of rapidly growing trees on short rotations removes more nitrogen than is added from the atmosphere by deposition and by biological fixation. Phosphorus, potassium, calcium, magnesium and other elements also are removed more rapidly by intensive harvesting than they are released from the soil mineral fraction and added by atmospheric deposition. Nutrient reserves in the solum vary widely as a result of differences in parent rock and soil-forming factors. Nutrient availability limits the growth of trees on many soils, and increased biomass removal will result in imbalance between demand and availability. Nutrient reserves which partly control the development of imbalance vary widely and are the result of parent material and soil-forming factors.

Acute deficiency of phosphorus has been noted in the Atlantic and Gulf Coastal Plains, where some soils require fertilization for survival and early growth of trees. Additional growth from nitrogen fertilization has been obtained for several species in almost every major forest area, and responses have been obtained from fertilization with other elements in many soils.

The nutrient status of forest soils includes a continuum from severe deficiency to adequate supply. Some highly productive sites have sufficient reserves and/or renewal processes to maintain productivity for several generations of trees whereas others need fertilization to be productive. What will happen to the supply of nutrients when this range of sites is managed to produce wood or biomass at near their maximum capacity? As return on investment permits, foresters, like producers of field crops, will probably apply fertilizers to obtain near maximum yield on some sites. There will also continue to be essentially unmanaged forests where the nutrient removal is not large as well as exploited forests where nutrients are removed at rates that cause a decline in productivity. A desire to produce efficiently on a sustained basis dictates that knowledge of the forest nutrient system be obtained and utilized in making decisions and formulating policies in forest management.

A nutrient balance sheet showing input and output indicates a site's long-term trend in nutrient status. At present the accuracy of input and output is questionable, as is availability of reserves. With the present state of knowledge, both input and output are probably underestimated, because direct atmospheric contributions to vegetation are difficult to determine and there are unmeasured nutrient leaks in most systems. Under the circumstances, we can only assume that errors in estimates of input and output approximately cancel each other, and that estimated outputs in excess of estimated inputs indicate a decline will occur in productivity of a site.

NUTRIENT BALANCES WITHOUT TREE HARVEST

Nutrients enter the forest system dissolved in precipitation, as gases, as deposition of particulates, by biological fixation, and by weathering of soil minerals. They leave in streamflow, deep seepage, gases, and aerosols. Data from several

sources show that output of potassium and calcium consistently exceeds input; however, the reverse occurs for nitrogen and phosphorus (Table 1).

Table 1. Average Annual Atmospheric Inputs, Outputs, and Net Gain or Loss of Elements from Several Temperate Forest Ecosystems with No Harvesting.[13]

Element	Environment	Input (avg)	Output (avg)	Net gain or loss (avg)	Range in net gain or loss
		kg/ha/yr			
Ca	Acid	--	11.4	-7.0	-0.1 to -20
	Calcareous[1/]	10.5	102.9	-92.4	-44.8 to -137
K	Inland	1.6	3.5	-1.9	-0.1 to -5
	Oceanic	2.6	5.5	-2.9	+0.7 to -8
N	Variable	7.9	2.0	+5.9	+17.5[2/] to +0.5
P	Variable	0.26	0.15	+0.11	+0.52 to -0.2

[1/] Includes carbonates and mafic parent materials.

[2/] Includes atmospheric nitrogen fixation.

Nitrogen input as reported here is primarily the ammonium and nitrate form which is rapidly incorporated in living organisms and held in the system by cycling processes. Phosphorus is held by cycling processes and in slightly soluble compounds of iron, aluminum and calcium. The cycling process of nitrogen and phosphorus provides for their accretion in the forest system, rather than reduction as for calcium and potassium.

In addition to atmospheric nitrogen input in precipitation, 5 kg/ha/yr may be added by non-symbiotic nitrogen-fixing organisms and considerably larger quantities by symbiotic systems. Nitrogen from these sources is also cycled within the forest system and held against leaching losses.

Nutrient input to the available fraction from mineral soil and parent rock has been measured by mass balance studies of watersheds.[5] For example, calcium release from weathering is estimated as the difference in the sum of loss in the stream plus changes in the soil and plants minus the amount in deposition from the atmosphere (weathering = steam loss + Δ soil and plant - atmospheric deposition). Clayton[5] showed estimates of weathering rates by several investigators (Table 2). Annual weathering rates controlling the potential for exploitation vary for potassium from about 1.5 kg/ha in the Oregon Cascades to 11 kg/ha in Brookhaven, N.Y. and for calcium from 1.3 kg/ha in the Maryland Piedmont to 86 kg/ha for dolomitic parent material in the White Mountains of California.

In general, losses in undisturbed systems approximately equal input over long periods of time.

FOREST DISTURBANCES AND LOSSES THROUGH WATER AND THE ATMOSPHERE

The nutrient balance in the forest system is disturbed by natural or man-related events such as burning and harvesting which increase nutrient transport in water and air in addition to the amounts removed in biomass harvest. The former losses, though not obvious, may exceed those of the biomass harvest itself. Fires volatilize significant amounts of

Table 2. Comparisons of Elemental Release from Rock Weathering Using Mass Balance Techniques.[4]

Location	Rock type	K	Ca
		kg/ha/yr	
White Mountains, California	Dolomite	4	86
White Mountains, California	Adamellite	8	17
Cascades, Oregon	Tuffs/breccias	1.6	47
Piedmont, Maryland	Schist	2.3	1.3
Hubbard Brook, New Hampshire	Moraine/gneiss	7.1	21.1
Brookhaven, New York	Outwash sands	11.1	24.2

nitrogen and sulfur and produce ash that may become airborne or transported in the water as dissolved salts and sediment. Effects of fire on nutrient output vary in relation to fire intensity, amount and type of fuel, topography, and soil. Wildfires of high intensity may cause a large nutrient output from the site. Burning for site preparation may cause nutrient losses, but periodic prescribed burning of established stands seems to have little effect on site nutrients.

Cutting vegetation may increase nutrient output by increasing erosion and water-soluble transport. Losses were very severe when all vegetation was killed but not removed and new growth was prevented with herbicides at the Hubbard Brook Experimental Forest in New Hampshire.[2] The elimination of growing vegetation prevented the conservation of site nutrients by plants and resulted in their being lost from the site. Other investigations of

commercial clearcuts in the Hubbard Brook area indicated nitrogen and calcium losses of about 90 and 100 kg/ha during the first 2 years after clearcutting northern hardwood forests on sandy podzols with accumulated organic surface layers over granitic rock.[11] The majority of reports show nutrient losses following cutting much lower than for the Hubbard Brook studies, and in some studies of clear cutting, patch cutting, and strip cutting losses were minor or unmeasurable.[13] Plant accumulation is the major process for control of leaching.[16] The major driving force for nutrient loss following cutting seems to be nitrification, with the subsequent leaching of the nitrate anion and cations.[10]

An increase in harvest intensity can be expected to decrease soluble nutrient losses but increase sediment transport. The greater biomass removal reduces the amount of organic residue that will be subject to decomposition and nutrient release; however, the increased potential for erosion should always be considered. Nutrient losses following harvest are expected to be greater for hardwood than for conifer stands because the hardwood residues decompose more rapidly. Where an understory is absent or vegetation control is contemplated, conifer biomass harvest has the potential for relatively large losses of soluble nutrients and particulate matter. Losses may be small, however, because nitrification is low and decomposition is slow in conifer litter. Although there are processes that cause nutrient losses from a forest system into the atmosphere and water, excessive losses can be avoided by applying some of the recent knowledge about contributing factors.

NUTRIENT REMOVAL IN HARVEST

Tree species, rotation age, site productivity, and harvesting intensity influence the amount of nutrients removed from the site in timber harvest. Nutrient concentrations in hardwoods are greater than in conifers; therefore, for an equal biomass yield, the nutrient removal rate is about double. Annual nutrient uptake by trees is several times the annual removal rate in biomass harvest, because uptake is the sum of nutrients assembled in the harvested tree parts and nutrients returned to the soil through mortality of leaves, branches, roots, and other components. Annual nutrient requirements for highly productive hardwoods are similar to those for field crops, but the removal rates by harvest are usually much smaller for hardwood than for crops.

Intensively managed plantations produce 10,000 to 20,000 kg/ha/yr of dry biomass, but yields of 6,000 to 10,000 kg/ha are more likely in typical plantations (Table 3). The higher yields are generally produced by fertilizing and even irrigating. The extremely high yield of 16,600 kg/ha/yr by loblolly pine (Pinus taeda L.) was produced without irrigation and fertilization on land previously fertilized for crop production.[8] Annual yields of 10,000 to 20,000 kg/ha will approximately double the current output in harvest.

Annual nitrogen uptake by loblolly pine was estimated at more than 100 kg/ha,[18] whereas the nitrogen increment in the aerial parts was 16 kg/ha. The uptake was 6.25 times the biomass increment. With the same ratio of uptake to increment, the outstandingly high yielding 10-year-old stand with an increment of 57 kg/ha/yr of nitrogen would require approximately 350 kg/ha/yr in total uptake. This is probably a high estimate, but it provides evidence that high tree yields require a large uptake of elements.

Short rotations of intensively cultured hardwood are generally planted on more fertile soil than are conifers. Cottonwood (Populus deltoides Michx.) plantations yield large amounts of biomass and remove relatively large amounts of phosphorus, potassium, and calcium. Except in the very demanding 4-year-old cottonwood rotation, nitrogen removal is comparable to that of loblolly pine.

A 4-year rotation of cottonwood removes approximately twice as much nitrogen, phosphorus, potassium, and calcium as a 12-year rotation with the same annual biomass yield. A comparison of 20 and 40-year

Table 3. Average annual nutrient output Through Harvest of Aerial Parts by Species, Age and Harvest Intensity.

Species and reference	Age	Harvest intensity	Biomass	N	P	K	Ca
	Years			--------- kg/ha/yr ---------			
Populus deltoides	4	Above ground (dormant)	8,525	32	5.5	30	66
	12	Above ground (dormant)	8,716	18	2.4	14	32
	20	Above ground (dormant)	6,800	13	2.4	14	29
Pinus taeda[18]	16	Above ground	9,750	16	1.9	10	12
Pinus taeda[14]	20	Stem	Good site	15	0.8	8	9
	20	Above ground	Good site	19	1.4	10	10
	40	Stem	Good site	12	0.7	7	8
	40	Above ground	Good site	14	1.0	9	9
	10	Above ground	16,600	57	5.2	29	28
Pseudotsuga menziesii[5]	36	Stem	3,900	3.5	0.5	2.7	3.2
	36	Above ground	4,765	8.0	1.7	5.4	8.2
Pinus resinosa[1]	40	Stem	4,010	3.9	0.4	2.1	4.6
	40	Above ground	4,985	8.6	1.0	4.4	7.3
Picea glauca[1]	40	Stem	2,470	2.6	0.3	1.6	6.2
	40	Above ground	3,770	9.6	1.4	5.7	18.0

rotations of loblolly pine indicates a small difference in annual nutrient removal. Except for hardwood rotations of less than 5 years, complete tree harvest has a greater influence on nutrient removal than has rotation age.

Calculations based on data from Tables 1, 2 and 3 show that site balance would be negative with certain combinations of output and input. Table 1 shows 5.9 kg/ha average annual net gain of nitrogen to forest systems. This gain meets the demands of stem harvest of Douglas fir [Pseudotsuga menziesii (Mirbel) Franco], red pine (Pinus reninosa Ait.) and white spruce (Picea glauca Moench.) but not that resulting from the harvest of other species. Production of alder or other trees which are symbiotically associated with nitrogen-fixing microorganisms or the culture of nitrogen-fixing plants during regeneration of the trees could balance output and input.

The annual gain of approximately 0.1 kg P/ha from excess atmospheric deposition over solution losses fails to compensate for any commercial harvest. Soil tests for available phosphorus are fairly reliable and tests show a low level in many forest soils. Total phosphorus in the surface 50 cm of soil may be as low as 50 kg/ha in Coastal Plain soils. Even with complete exploitation of soil phosphorus, this amount would not produce two rotations of a highly productive forest. Since phosphorus-bearing soil minerals are low in solubility, fertilization is essential on many sites and will be required even more as production increases.

Potassium demands by harvest (Table 3) exceed the sum of net gain (Table 1) and weathering release (Table 2) for a number of species-soil combinations. As production increases, there is potential for development of potassium deficiencies in other areas similar to those reported in New York.[9] The mass balance technique seems to underestimate release in weathering because potassium is fixed in a nonexchangeable form which has an intermediate availability to plants. Even though potassium release by weathering is very low in the Piedmont, potassium deficiency for loblolly pine has not been reported in the area. Potassium fertilization is widely required for crop production, and only the rapid cycling of the element provides a sufficient supply for trees on many soils with a low native supply.

Hardwoods require more calcium than do conifers, and site output of the element from harvest is approximately three times as great for hardwood as for conifer culture. Annual release of calcium by weathering and loss in solution from calcareous soils are about double the amount removed in harvest of hardwoods, indicating that an adequate supply is available in these soils. In contrast, under the acid conditions as found in the Maryland Piedmont soil, the weathering rate estimated by mass balances is almost nil, and site loss in solution and harvest indicates an insufficient supply for either hardwood or pine. The mass balance technique does not seem to correctly reflect the supply to pine as indicated by the lack of reported calcium deficiencies.

In some cases production can be increased by fitting demands (Table 3) to supplies (Tables 1 and 2). On many sites, however, the balance must be met by cultural practices, such as limiting biomass harvest, fertilization, or planting nitrogen-fixing plants.

NUTRIENT BALANCE IN RELATION TO RESERVES

The sum of nutrients in the rooting zone of mineral soil, in the forest floor and in the roots is considered the site reserve. The ratio of reserve to imbalance of nutrient harvest and input is an indicator of the potential capacity of a soil to sustain the nutrient supply. Supply and availability regulate the use of nutrients, and nutrients become available through biological, chemical and physical processes. Thus, a site may become deficient in an element from a low availability of a large reserve or a depletion of the reserve.

Total nitrogen has been reported for the trees, forest floor and mineral soil of a number of forest stands (Table 4). The red alder (Alnus rubra Borg) site, as expected, has the largest proportion of

Table 4. Distribution and Proportion of N in Harvested Tree, (PP) Forest Floor Plus the Large Roots and (MS) Mineral Soil.[19]

Species and reference	Age	N-tree	N-FF	N-MS	FF/tree ratio	MS/tree ratio	FF + MS/tree ratio
		kg/ha	kg/ha	kg/ha			
Pseudotsuga menziesii[4]	36 BH[1/]	294	175	2809 (60 cm)	0.6	9.6	10.2
Picea rubens[17]	Uneven WTH[2/]	387	1465	559 (35 cm)	3.8	1.4	5.2
Pinus taeda[18]	16 BH	257	371	1753 (70 cm)	1.4	6.8	8.2
Alnus rubra[15]	34 WTH	413	1156	5454	2.8	13.2	16.0
Northern hardwood[3]	Uneven BH	351	1281	3600	3.6	10.2	13.8

[1/] BH is removal of above-ground minor vegetation and complete trees.

[2/] WTH is removal of complete trees.

nitrogen in the reserve pools of forest floor and mineral soil, and the northern hardwood stand ranks second, with conifers lower. Red spruce (Picea rubens Sarg.) has the lowest reserve to tree ratio with 5.2 times as much nitrogen in the forest floor + mineral soil as in the mature tree stand. The other conifer stands have total reserves intermediate between hardwood and spruce. The proportion of nitrogen in the forest floor is especially important, because it is subject to losses from mineralization and leaching and volatilization. This trend is borne out by large leaching losses of nitrogen and calcium from northern hardwood sites at Hubbard Brook, especially when there was no vegetation regrowth.

Phosphorus, potassium, and calcium reserves are often large in relation to net loss and removal rates but availability of these elements varies widely. Highly weathered soils may contain 0.2% and 0.6% calcium and potassium oxides as residuals of igneous rock parent material which is 5.1% calcium oxide and 3.1% potassium oxide.[12] Low phosphorus and potassium soils which require fertilizer have been noted earlier. To provide the required quantity of an element for a large uptake, availability as a percentage of the total must be greater on soils low in reserve; however, the opposite may be the case for phosphorus, potassium and calcium, because the more soluble materials have weathered.

Although the reserve supply may be a general indicator of the capacity of a soil to sustain availability at a given level, that level may not be sufficient for high productivity. More information must be obtained to relate availability to supply and periodic requirements of growing forests before we can predict the effects of high production on the soil. At the present, measures of nutrient status by foliar analysis and soil testing can provide some information useful for fertilizer prescriptions; however, more information is required to scientifically manage soil fertility for maximum forest production.

CONCLUSIONS

Nutrient budgets have been prepared for several forest types on different soils. Output is often greater than input, and it appears that intensive forestry practices create or increase deficiencies. The intensity or time of occurrence of these growth-limiting conditions cannot be predicted. Conservation, fertilization and use of nitrogen-fixing plants are effective ways to maintain and improve soil productivity. The most effective approach to maintaining and improving site productivity appears at present to be based on a general knowledge of site nutrient balance supported by nutrient availability data from foliar analyses and soil tests.

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